

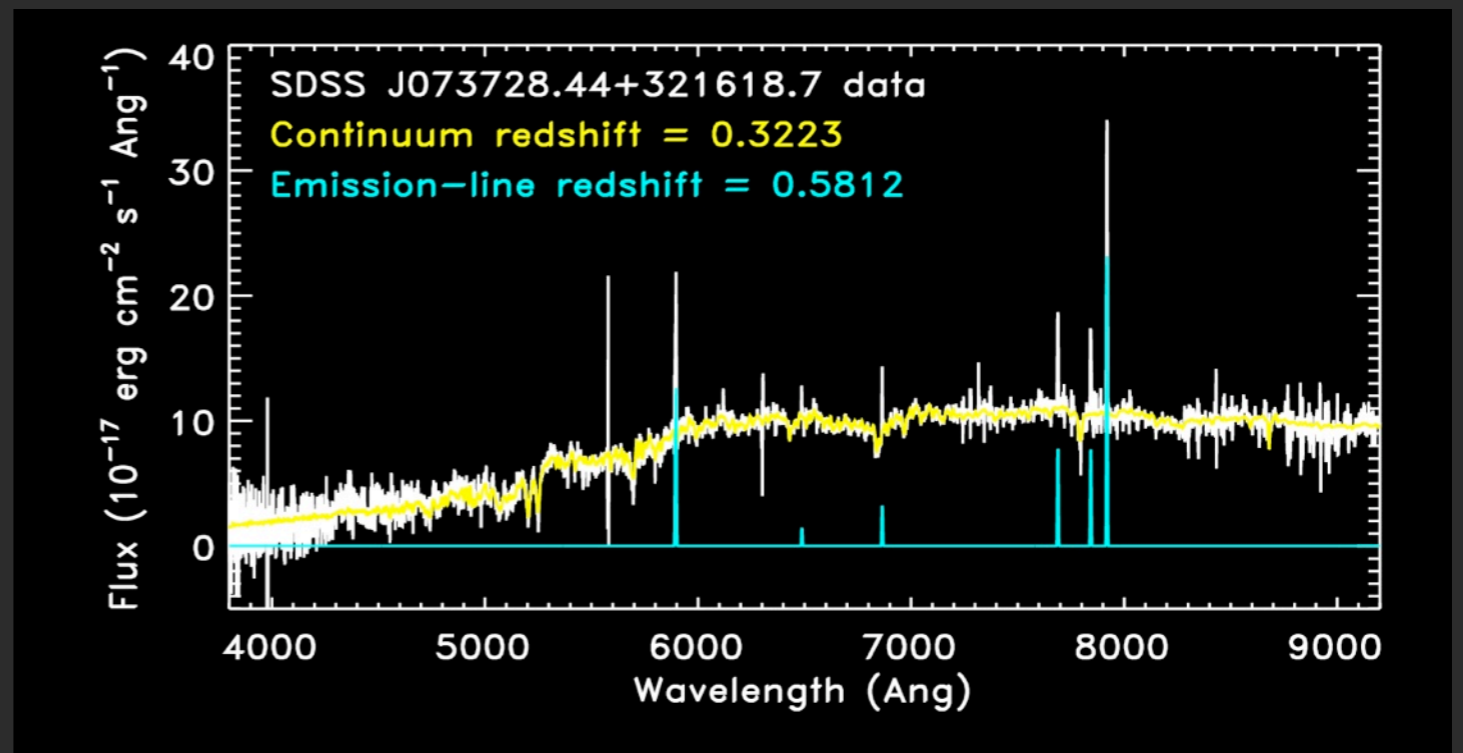
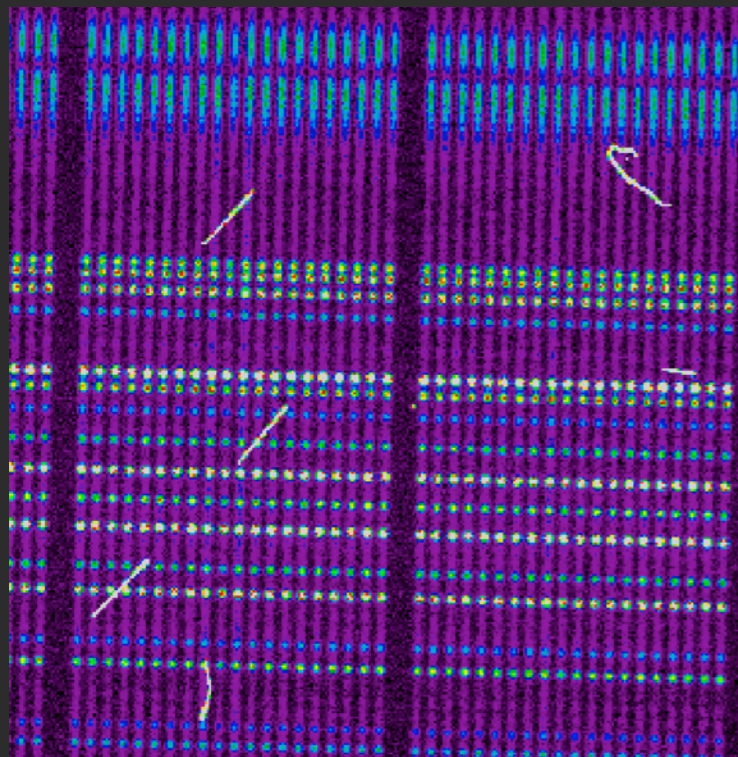
Spectro-Perfectionism: An Algorithmic Framework for Photon Noise-Limited Extraction of Optical Fiber Spectroscopy

Adam S. Bolton
University of Utah
Department of Physics & Astronomy
BigBOSS - LBL - 2009 Nov 20

Spectro-Perfectionism:

What is the *right*
way to go from this:

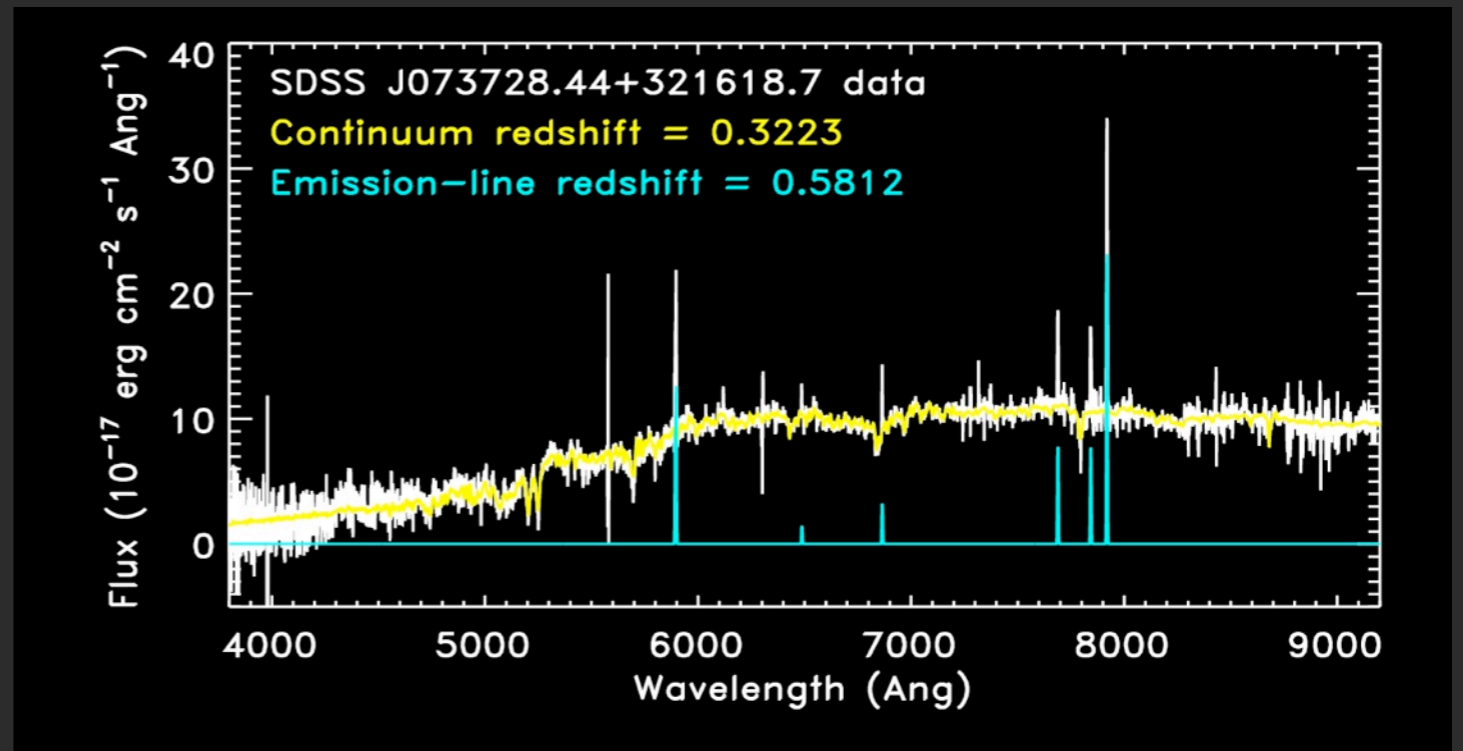
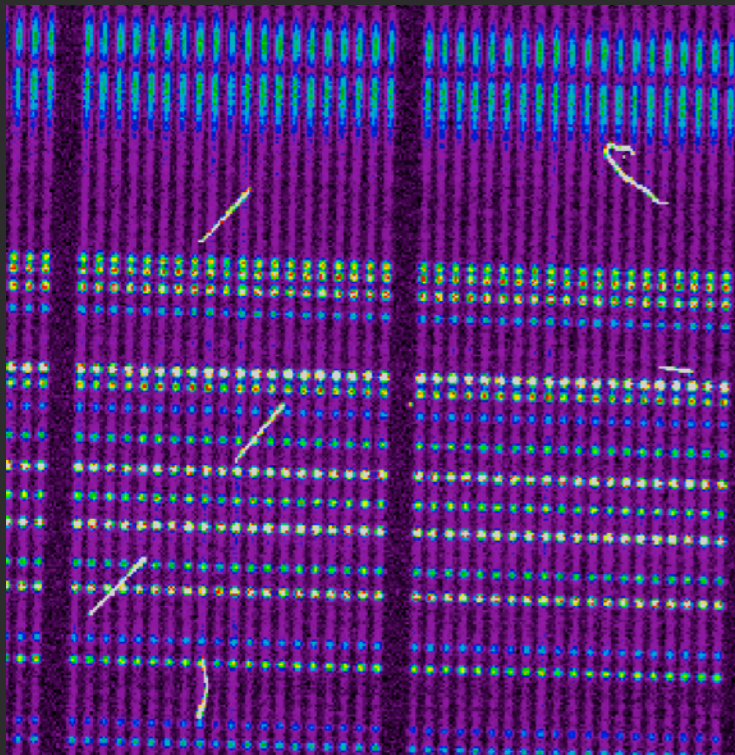
... to this:



?

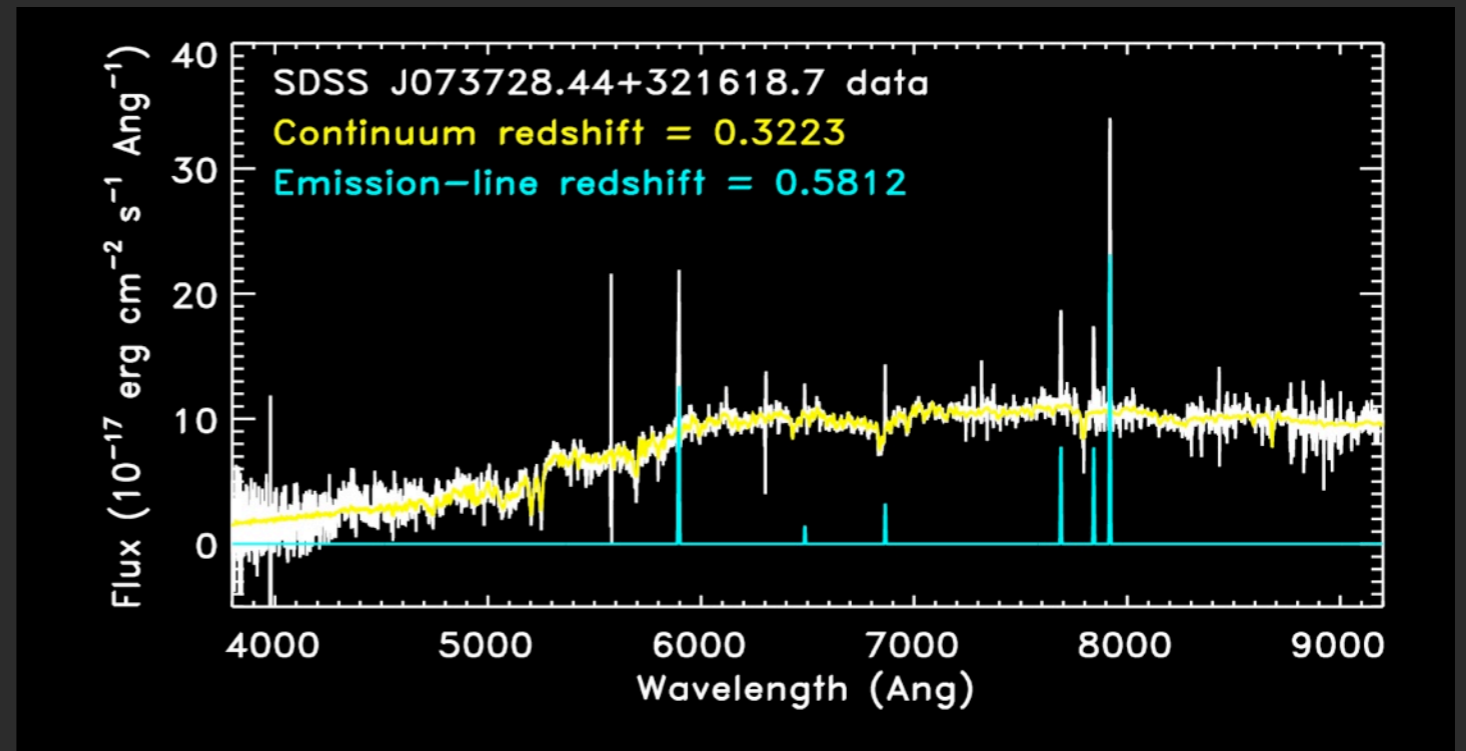
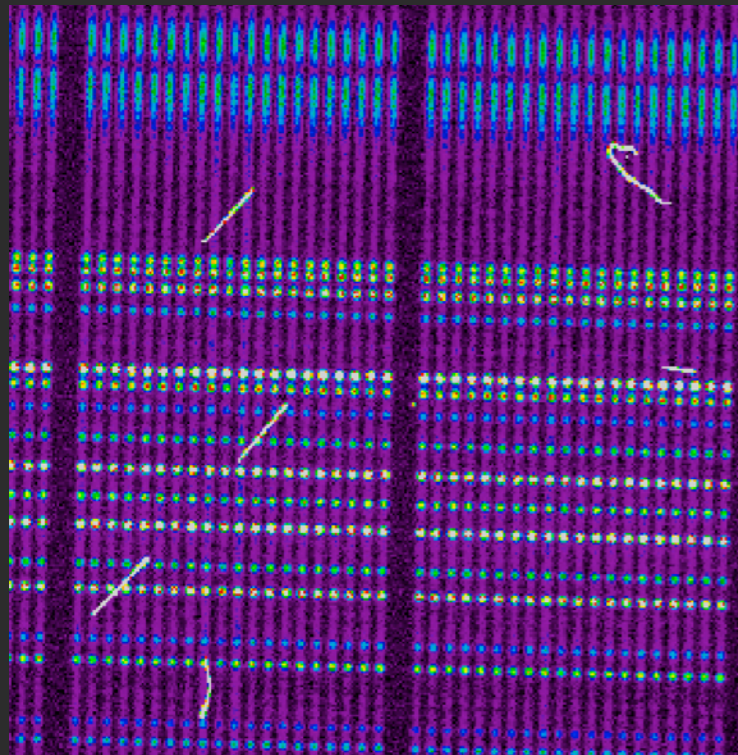
Spectro-Perfectionism:

Bolton & Schlegel (2009, PASP, submitted)
arXiv:0911.2689



Forward v. Inverse:

Two different ways to think of the same problem



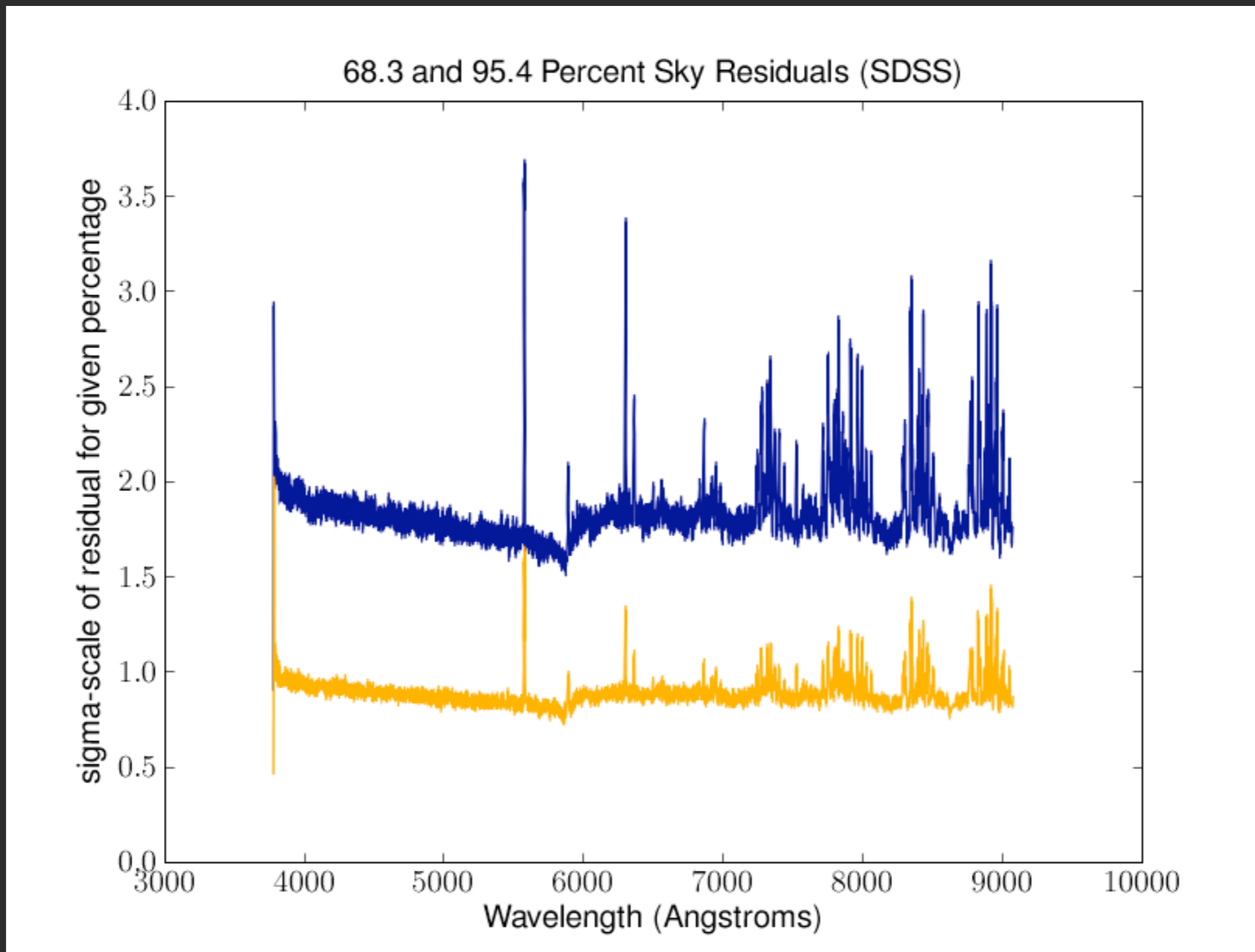
Hasn't this problem been solved?

Yes, but not well enough.

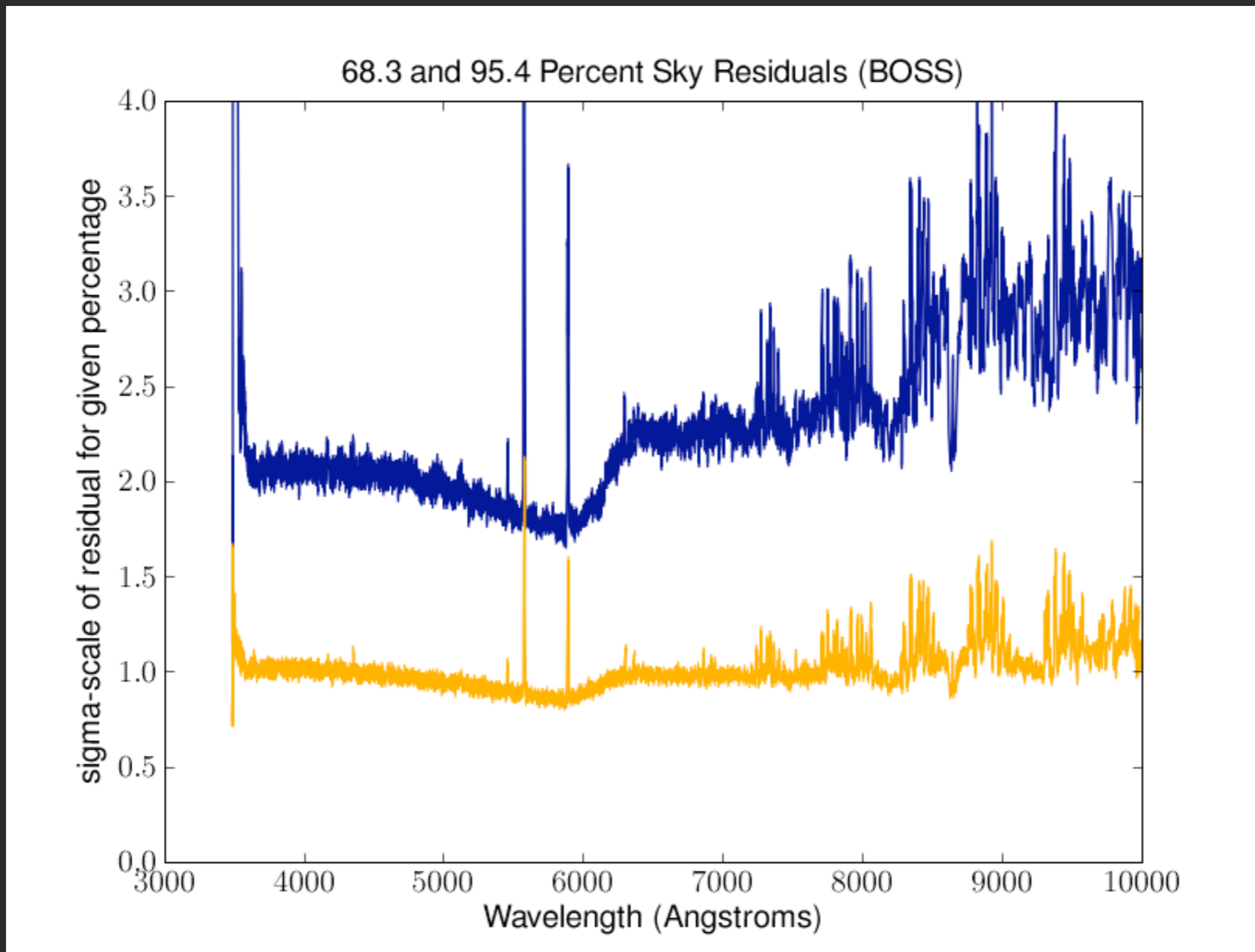
As the objects get fainter, the sky stays just as bright as ever

If you want statistical noise-limited spectra using fibers, the answer is no!

Systematics of sky subtraction



Systematics of sky subtraction



The general problem

$$A_{jk} (f_k + s_k) = p_j + n_j + b_j$$

A_{jk} : Calibration matrix

f_k : Input flux vector

s_k : Input background vector

p_j : Pixel count (data) vector

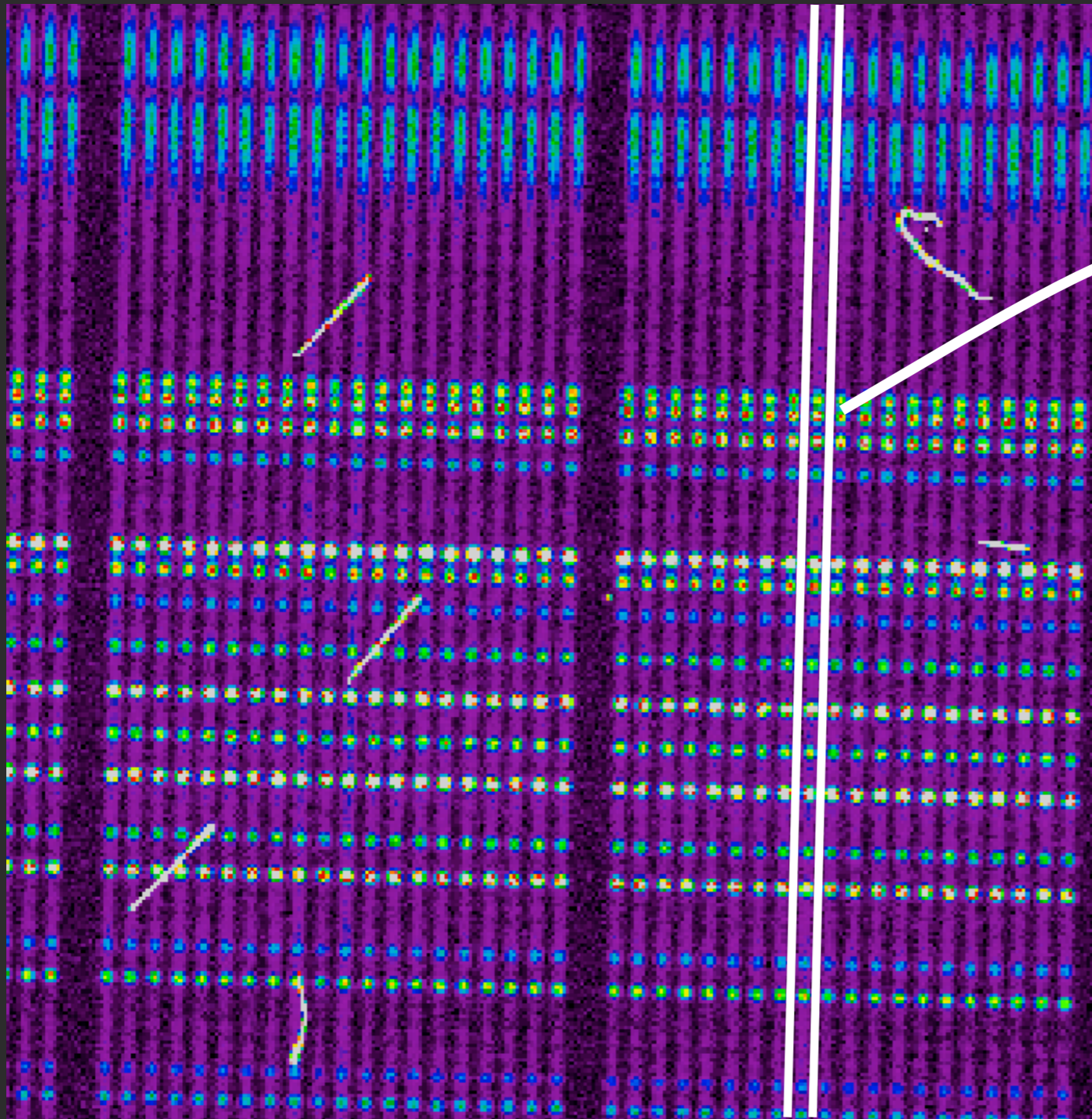
n_j : Pixel noise vector

b_j : Internal background vector

Desirable extraction features

- Define in terms of objective scalar optimization
- Generate noise-limited model of all 2D frames
- Allow optimal weighting
- Do not degrade resolution
- Characterize resolution accurately
- Avoid correlations in extracted 1D samples
- Propagate errors correctly
- Preserve these properties in multi-frame coadds
- Allow foreground estimation and subtraction in the presence of optical non-uniformities
- Deliver something that fits an astronomer's understanding of “the extracted spectrum”
- Make it easy to implement

Boxcar extraction



- Draw two lines
- Sum enclosed counts
- Call that your spectrum

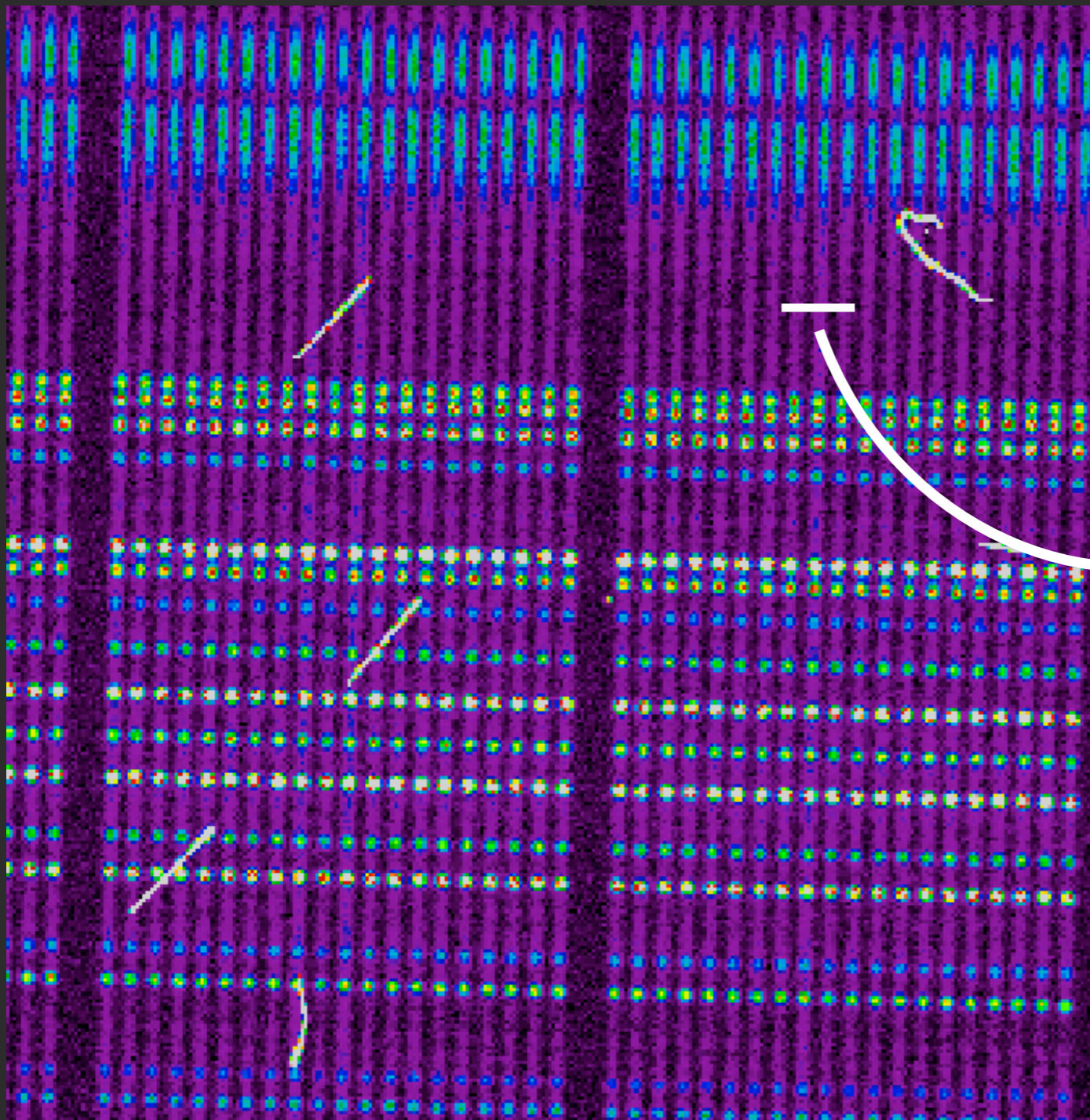
The “quick and dirty” method.

Boxcar scorecard

- ☐ Define in terms of objective scalar optimization
- ☐ Generate noise-limited model of all 2D frames
- ☐ Allow optimal weighting
- ☐ Do not degrade resolution
- ☐ Characterize resolution accurately
- ☒ Avoid correlations in extracted 1D samples
- ☒ Propagate errors correctly
- ☐ Preserve these properties in multi-frame coadds
- ☐ Allow foreground estimation and subtraction in the presence of optical non-uniformities
- ☒ Deliver something that fits an astronomer's understanding of "the extracted spectrum"
- ☒ Make it easy to implement

Optimal extraction

Hewett et al. 1985;
Horne 1986



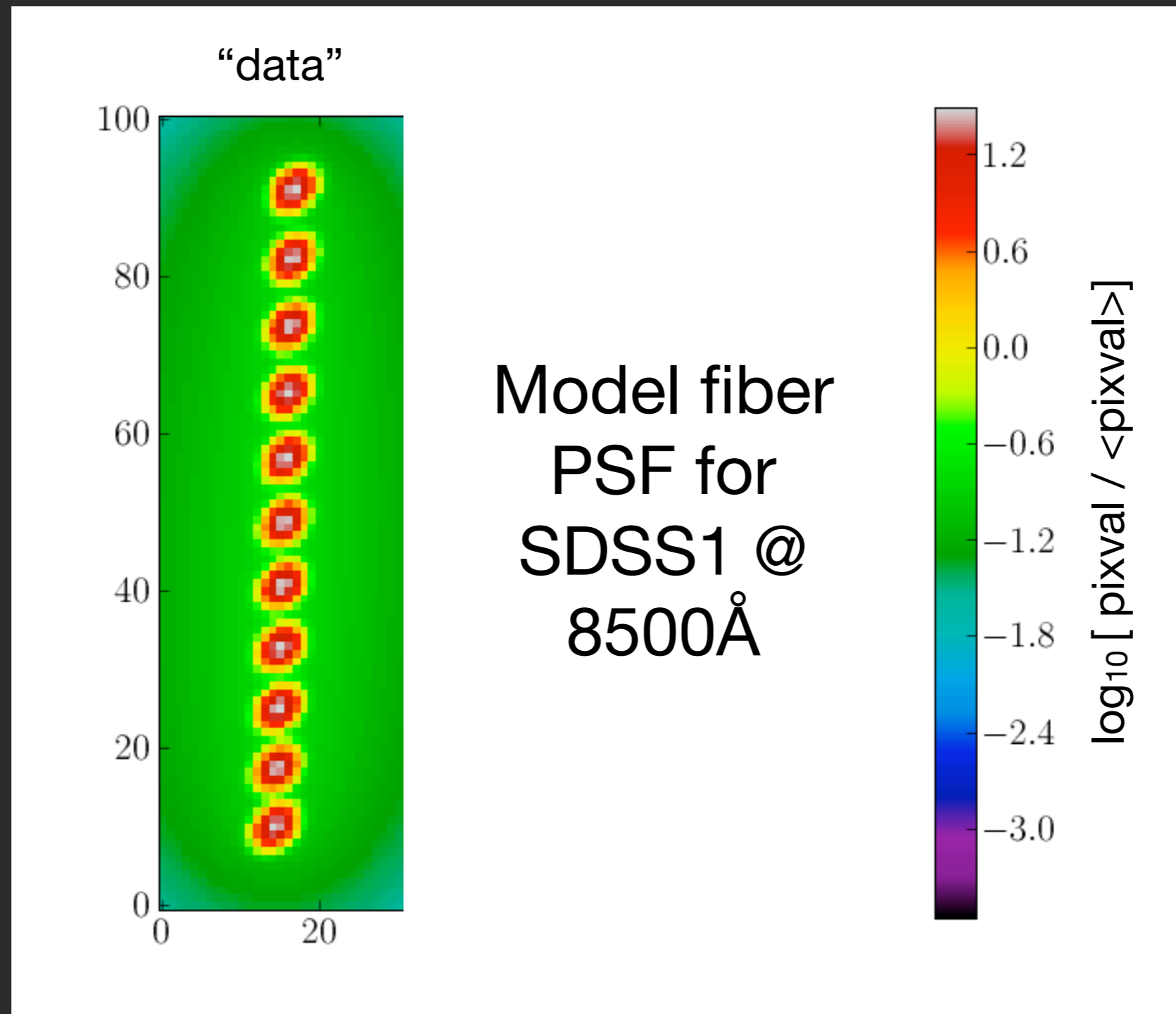
- Determine cross-sec'n
- Weighted amplitude fit
- Call that your spectrum

The current standard in extraction (e.g., SDSS: Burles & Schlegel)

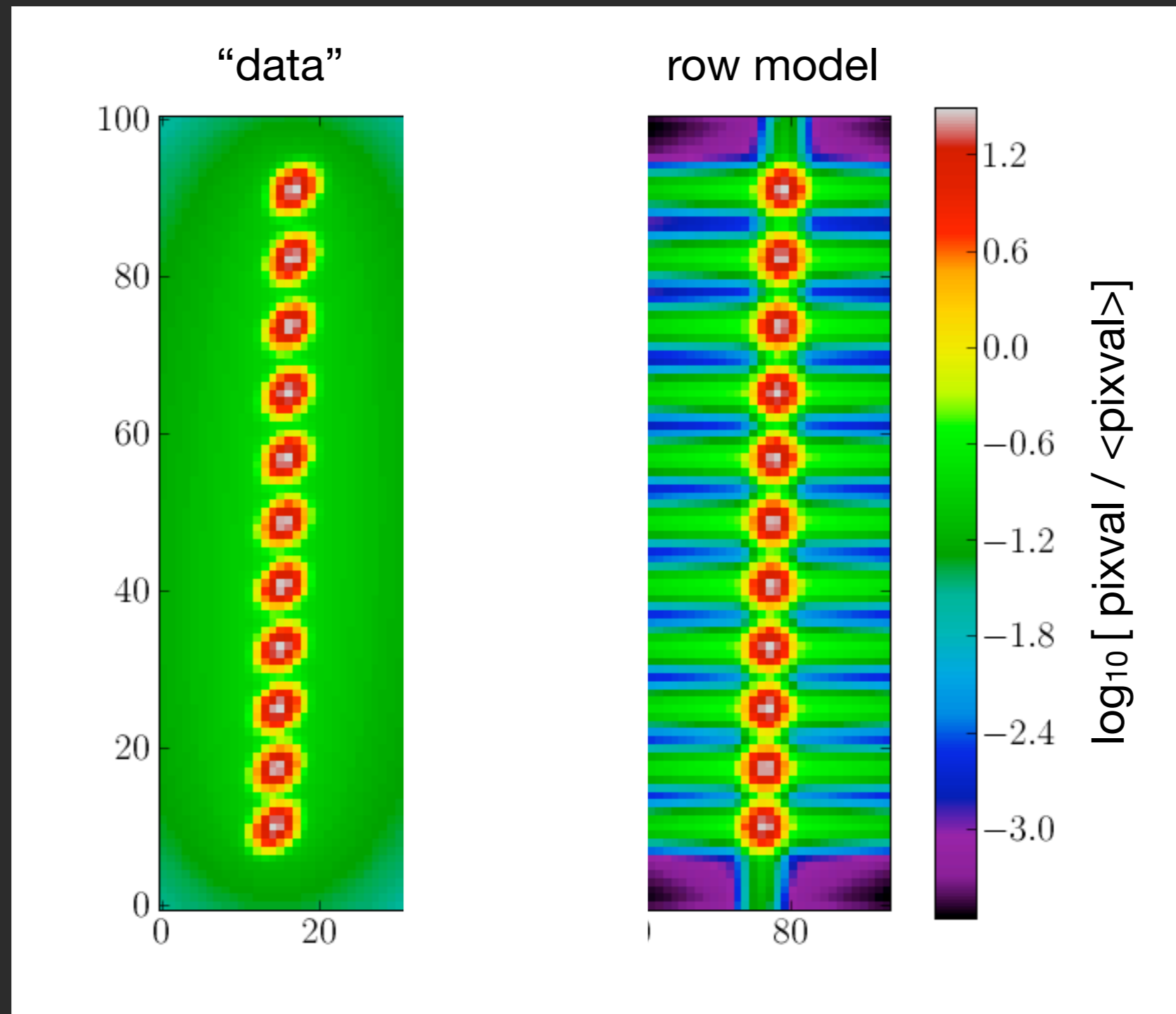
Optimal-extraction scorecard

- ☒ Define in terms of objective scalar optimization
 - ☒ Generate noise-limited model of all 2D frames
 - ☒ Allow optimal weighting
 - ☐ Do not degrade resolution
 - ☐ Characterize resolution accurately
 - ☒ Avoid correlations in extracted 1D samples
 - ☒ Propagate errors correctly
 - ☐ Preserve these properties in multi-frame coadds
 - ☐ Allow foreground estimation and subtraction in the presence of optical non-uniformities
 - ☒ Deliver something that fits an astronomer's understanding of "the extracted spectrum"
 - ☒ Make it easy to implement
- (almost)

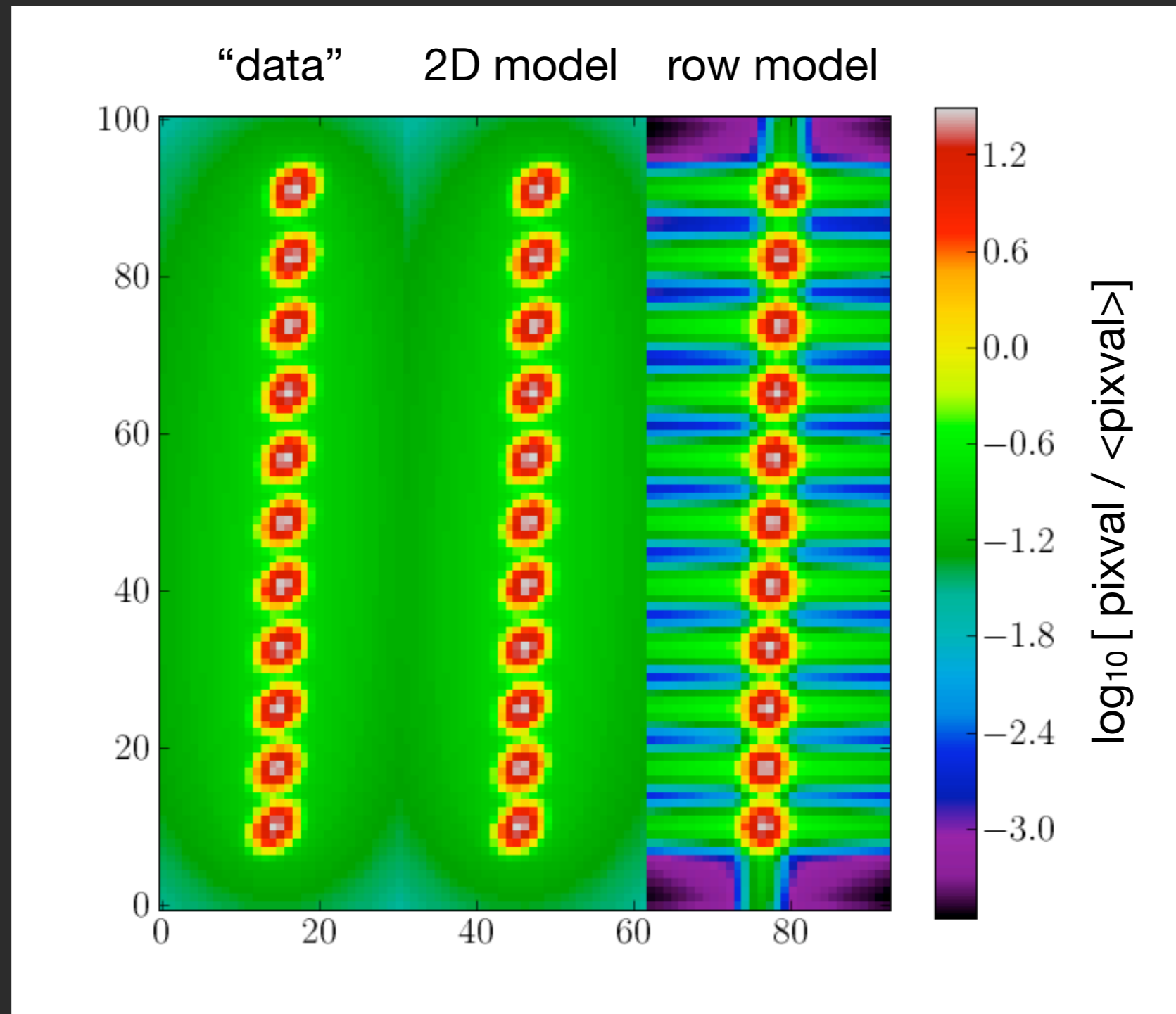
Extraction as image modeling



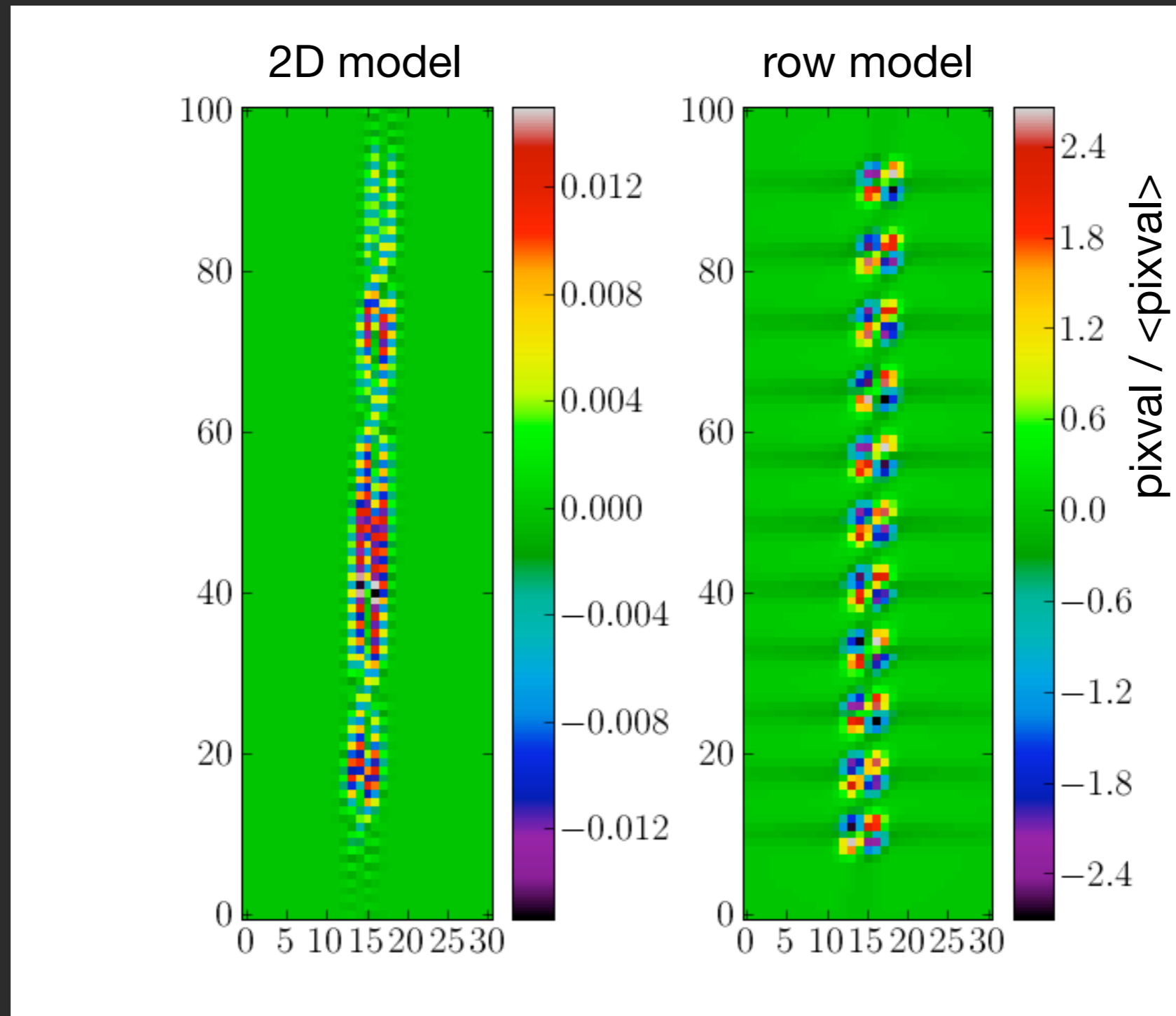
Extraction as image modeling



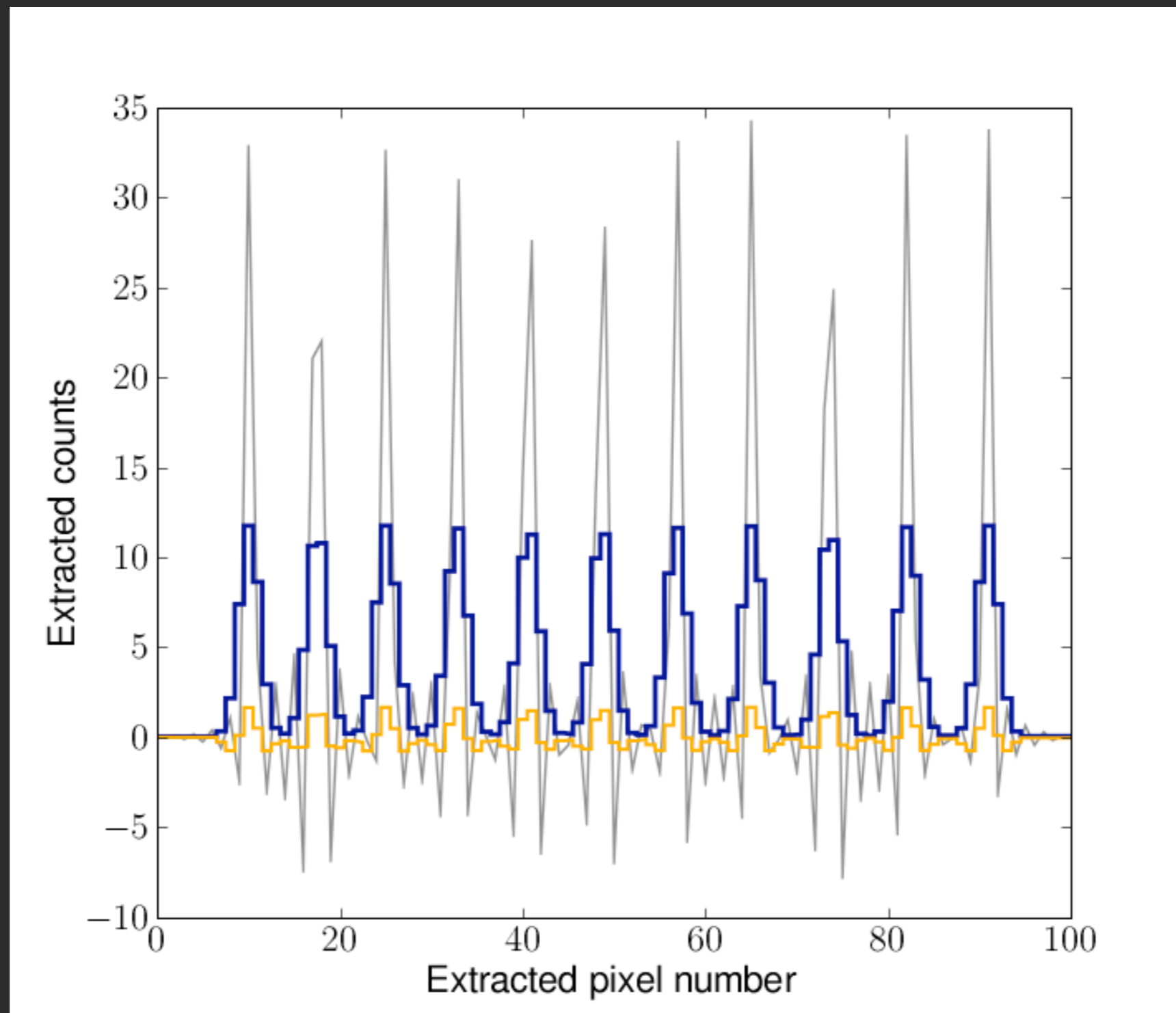
Extraction as image modeling



2D extraction model residuals



Deconvolution and reconvolution



Put resolution back into spectrum

The formal (deconvolved) solution:

$$\mathbf{f} = (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{N}^{-1} \mathbf{p}$$

Inverse covariance matrix of deconvolved spectrum:

$$\mathbf{C}^{-1} = \mathbf{A}^T \mathbf{N}^{-1} \mathbf{A}$$

Take unique non-negative square root of this matrix:

$$\mathbf{C}^{-1} = \mathbf{Q} \mathbf{Q}$$

Normalize along rows & factor out a diagonal matrix:

$$\mathbf{C}^{-1} = \mathbf{R}^T \mathbf{C}^{-1} \mathbf{R}$$

Note analogy

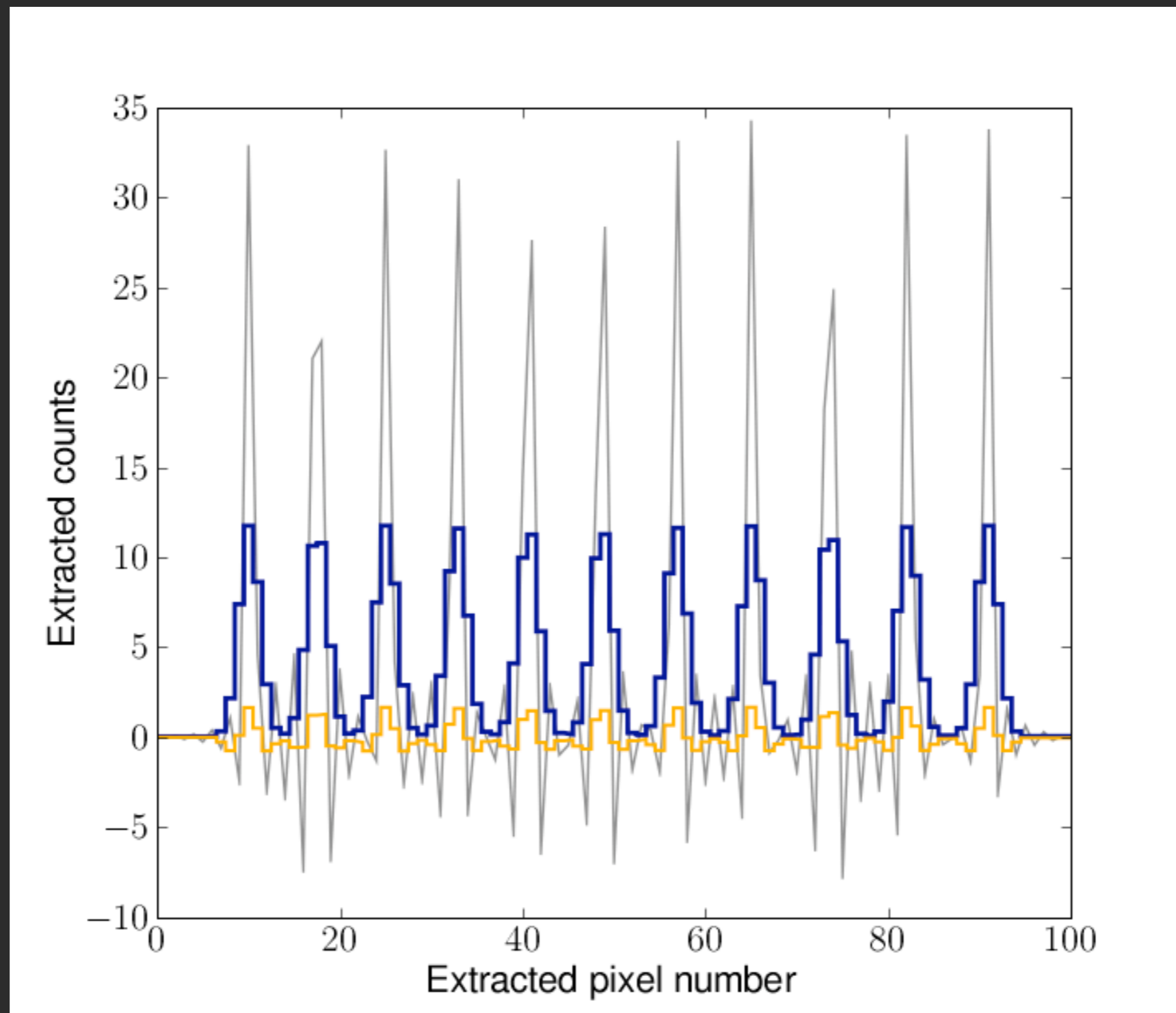
By consequence:

$$\mathbf{C} = \mathbf{R} \mathbf{C} \mathbf{R}^T$$

The reconvolved spectrum: what *would have been observed* by a 1D spectrograph with same resolution:

Uncorrelated errors $\rightarrow \mathbf{f} = \mathbf{R} \mathbf{f}$ Band diagonal

Deconvolution and reconvolution

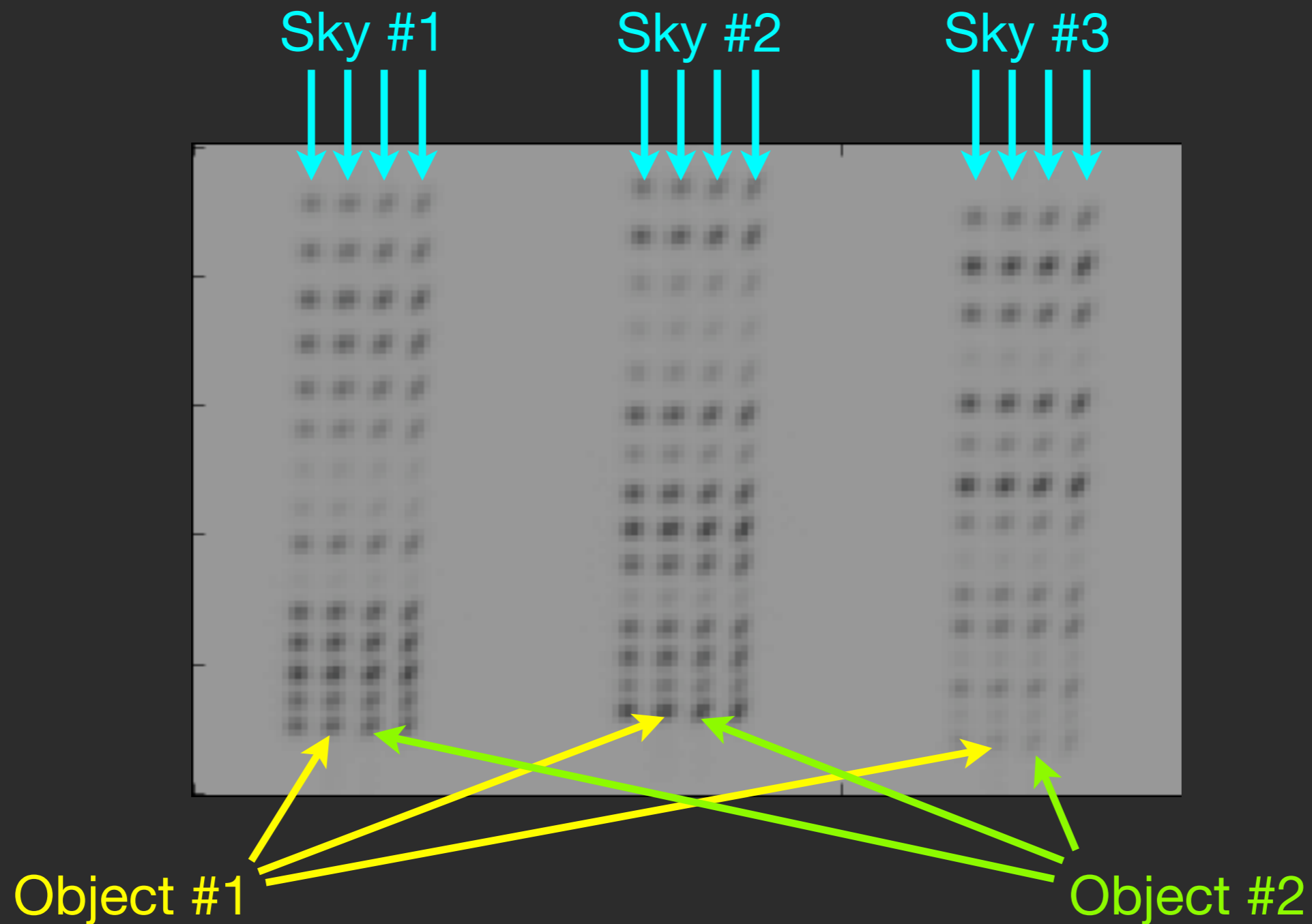


To make things interesting, add:

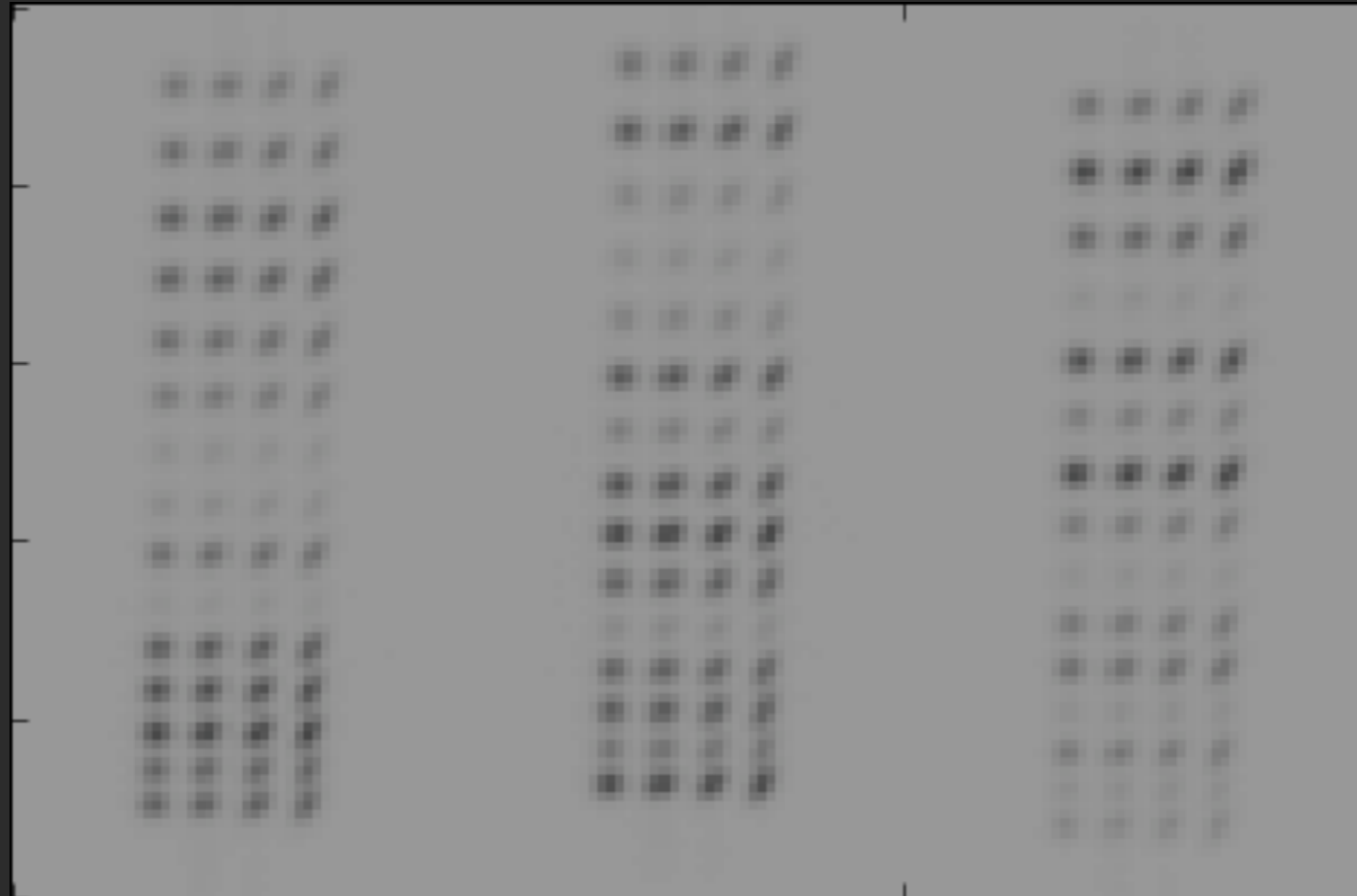
- Noise,
- Variable fiber PSF,
- Multiple frames with flexure/dither,
- “Sky”,
- Fiber-to-fiber crosstalk

***Can do extraction, coaddition,
and sky subtraction in one shot!***

Multi-frame, multi-fiber simulated data



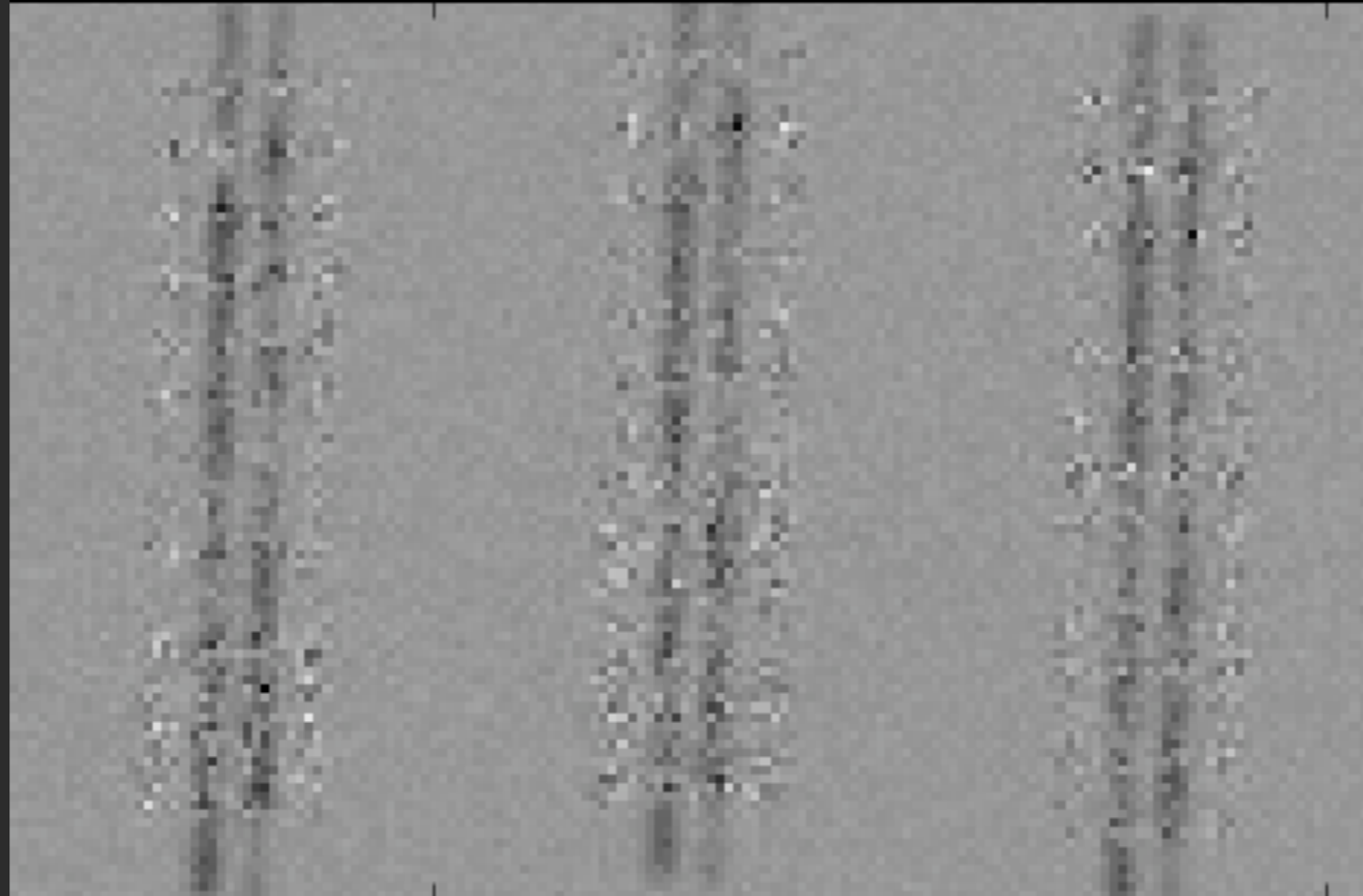
Multi-frame, multi-fiber simulated data



$$\text{Objflux} = \text{Skyflux} / 20$$

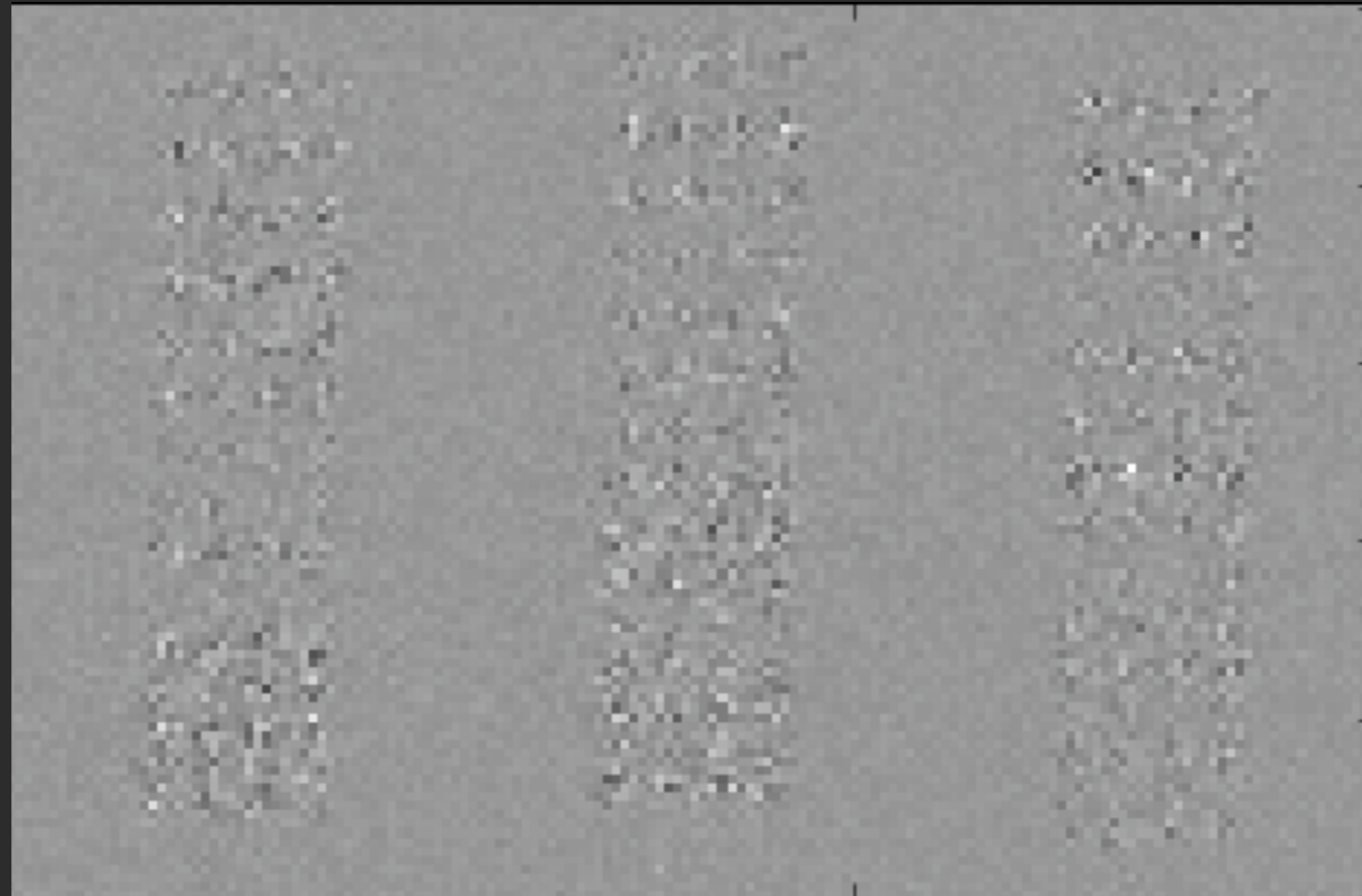
$\text{ObjSNR} \approx 5$ (per extracted sample, sky-noise limited)

Sky model decomposed & removed



(Grayscale stretch X 40 relative to previous)

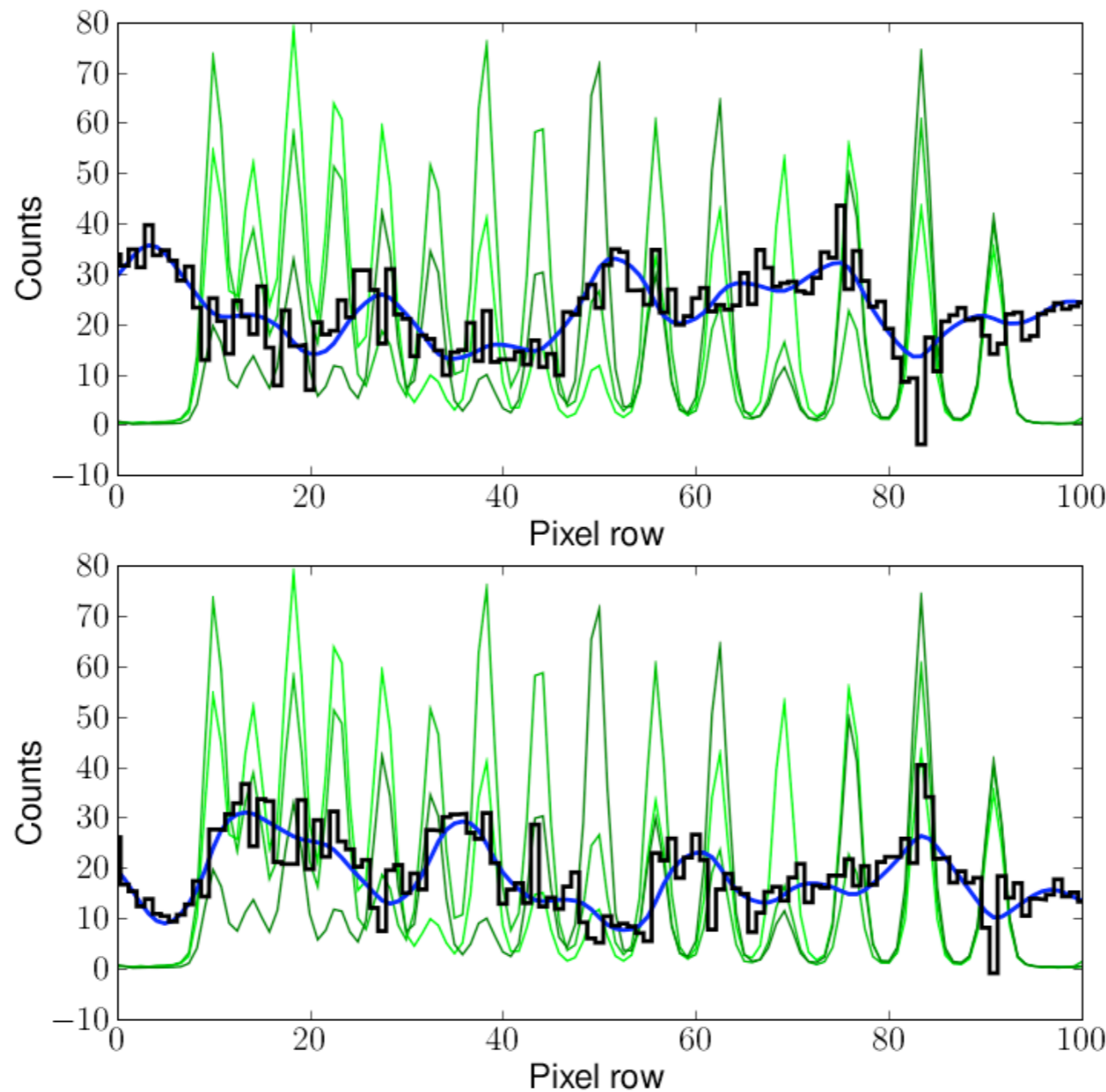
All models removed



Consistent with pure noise

Extracted objects + skies

Sky scaled
down by a
factor of 20
in plot



RMS error-
scaled
residuals of
unity

Spectro-perfectionism scorecard

- ☒ Define in terms of objective scalar optimization
- ☒ Generate noise-limited model of all 2D frames
- ☒ Allow optimal weighting
- ☒ Do not degrade resolution
- ☒ Characterize resolution accurately
- ☒ Avoid correlations in extracted 1D samples
- ☒ Propagate errors correctly
- ☒ Preserve these properties in multi-frame coadds
- ☒ Allow foreground estimation and subtraction in the presence of optical non-uniformities
- ☒ Deliver something that fits an astronomer's understanding of "the extracted spectrum"
- ☐ Make it easy to implement

The biggest headache:

Fiber-to-fiber cross-talk couples all spectra.

For each BOSS spectrograph-plate, we have:

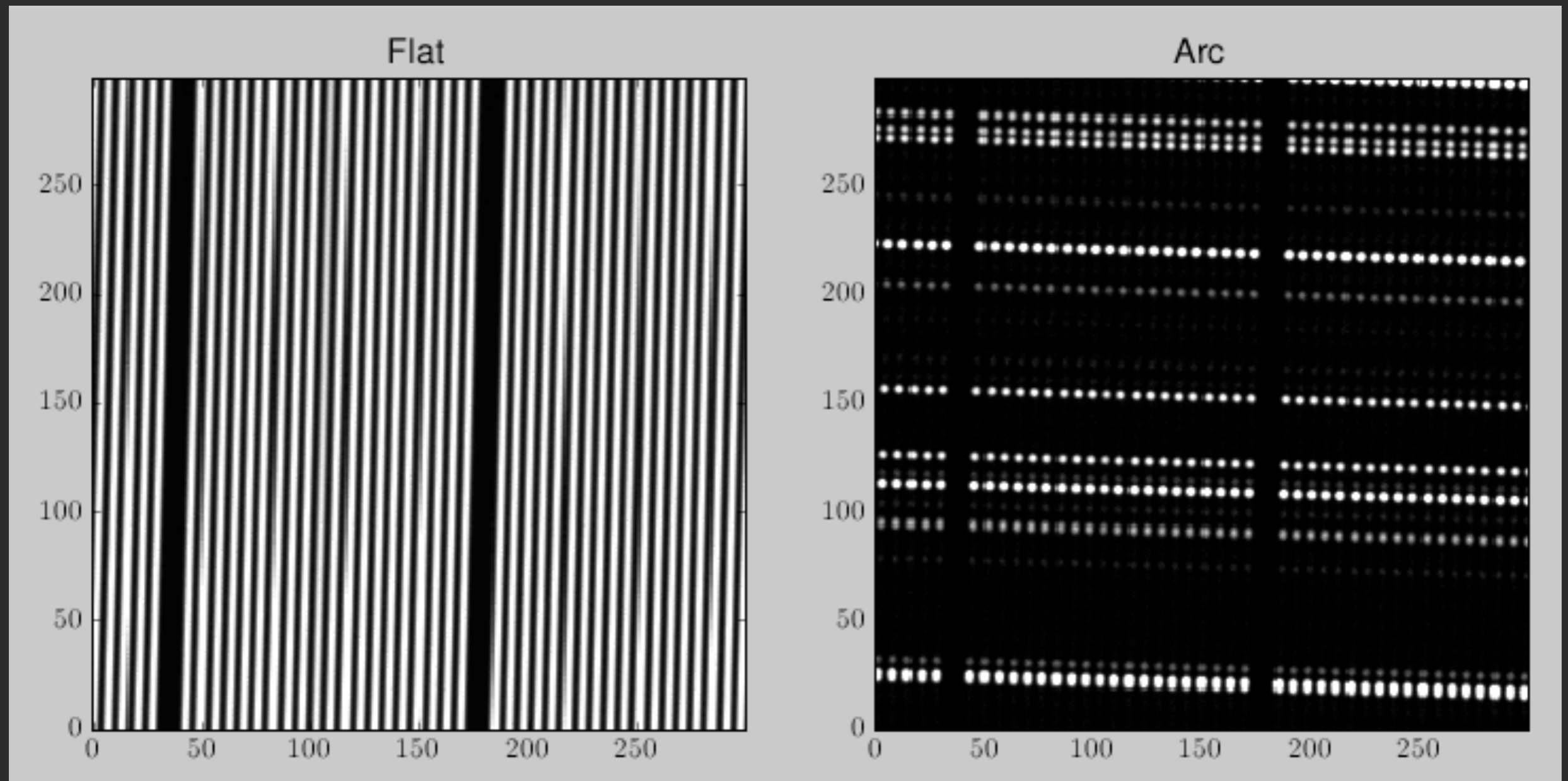
500 spectra \times 6000 sampling points \times 4 frames

\Rightarrow ***12 Million coupled equations to solve!***

Fortunately the matrix is sparse...

(Sampling also swept under rug here, but see paper...)

The challenge to calibration and design



The challenge to calibration and design

Current calibration facilities may not permit a sufficiently accurate determination of A_{jk}

=> New calibration regimes and equipment (high-wattage monochrometer or tunable laser)

(c.f. Stubbs & Tonry 2006)

Ultimately calls for a full integration of data analysis software with instrumental design software

=> Optimize *scientific* metrics in hardware

=> Tune instrument directly from data

=> “Use what you know” during analysis

The sociological challenge

Site selection:

Multi-year testing, remote locations, etc.

Telescope:

As large, reflective, and well-focused as possible

Instrument:

Expensive design, coatings, high-QE CCDs

Data calibration and analysis:

Some grad student will do it...

-or-

We'll just use IRAF...

Hopefully this model is a thing of the past...

Immediately TBD for BOSS

- Implement calibration-matrix determination from arcs, flats (+ tweaks from science frames)
- Implement extraction (using HPC?)
- Demonstrate noise-limited sky subtraction
- Onward! (APOGEE, BigBOSS, ...)

Summary

- Current extraction algorithms are inaccurate at a level that significantly degrades faint-object fiber spectra
- This problem can be solved with correct 2D modeling
- Handled right, resolution & covariance are optimal
- Extraction, coaddition, and sky subtraction in one shot
- Immediate application to BOSS => proof-of-technique for BigBOSS
- Accurate calibration is difficult but important
- Implementation of extraction may require HPC
- Interested in the coding effort (probably Python)?
Don't be a stranger!
- Check out the paper: [arXiv:0911.2689](https://arxiv.org/abs/0911.2689)



Thank You!



Department of Physics and Astronomy
ASTRONOMY AND ASTROPHYSICS
THE UNIVERSITY OF UTAH

BigBOSS - LBL - 2009-11-20

Adam S. Bolton

SNOWPAC & SNOWCLUSTER

March 23, 2010 - April 2, 2010



SNOWBIRD, UT

www.physics.utah.edu/snowpac